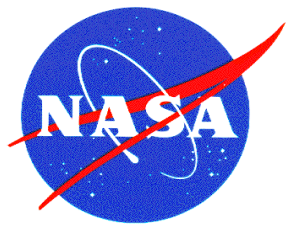
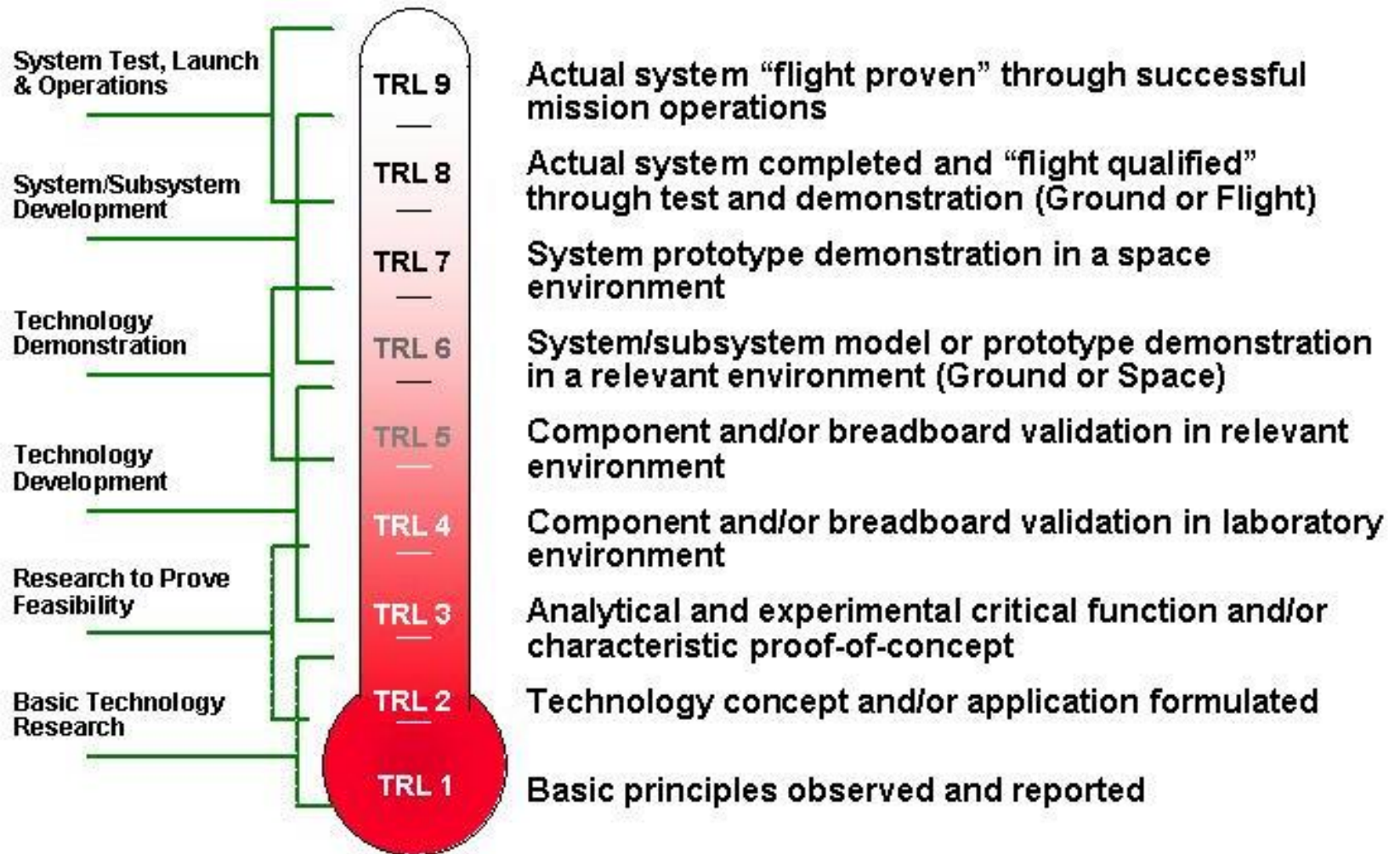


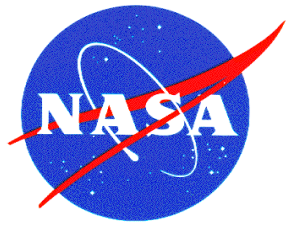
***Raising Nuclear Thermal  
Propulsion (NTP)  
Technology Readiness  
Above 3***

***Harold P. Gerrish Jr  
NASA Marshall Space Flight Center  
November 19, 2014***



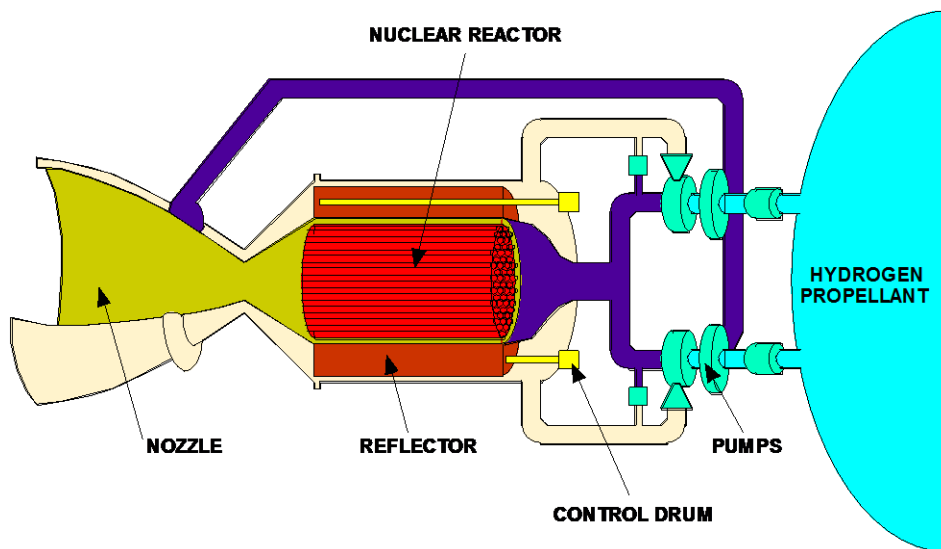
# ***NASA Technology Readiness Level (TRL)***





# How Does NTP Work?

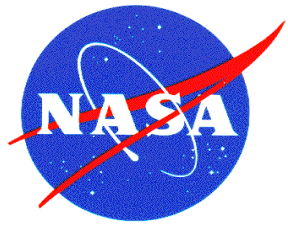
- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor:  $50,000 \text{ N} \approx 225 \text{ MW}_{\text{th}}$  at 900 sec
- Specific Impulse directly related to exhaust temperature: 830 - 1000 sec (2300 - 3100K)
- NTP Specific Impulse (~900 seconds) doubles over chemical rockets (~450 seconds) due to lower molecular weight of propellant



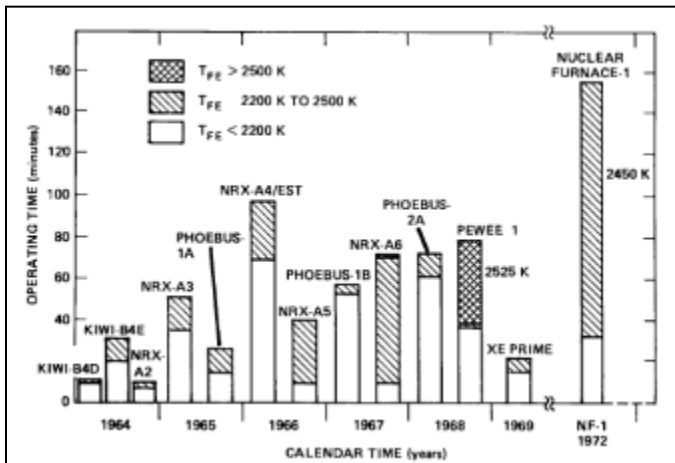
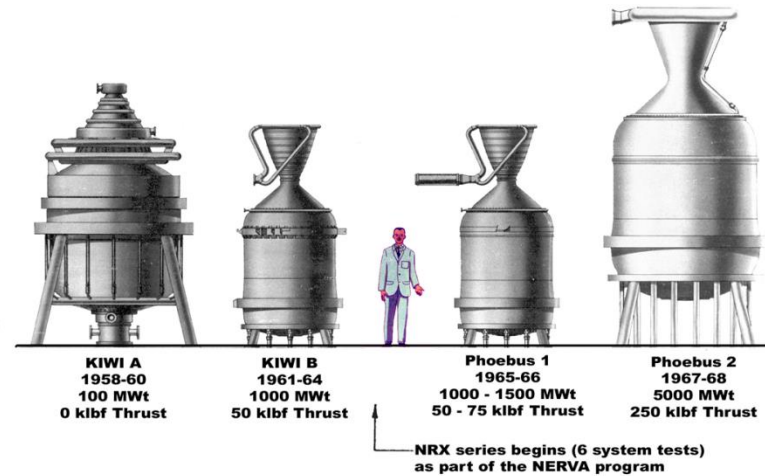
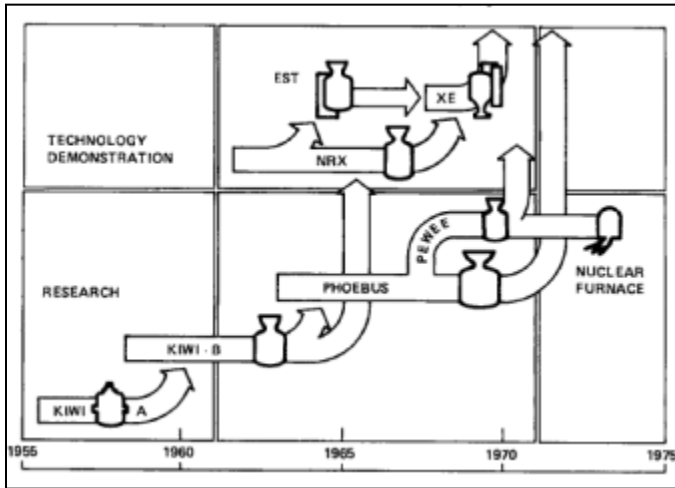
Major Elements of a Nuclear Thermal Rocket



NERVA Nuclear Thermal Rocket Prototype

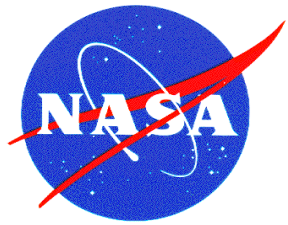


# Rover/NERVA Engines



20 NTP engines designed built and tested during Rover/NERVA

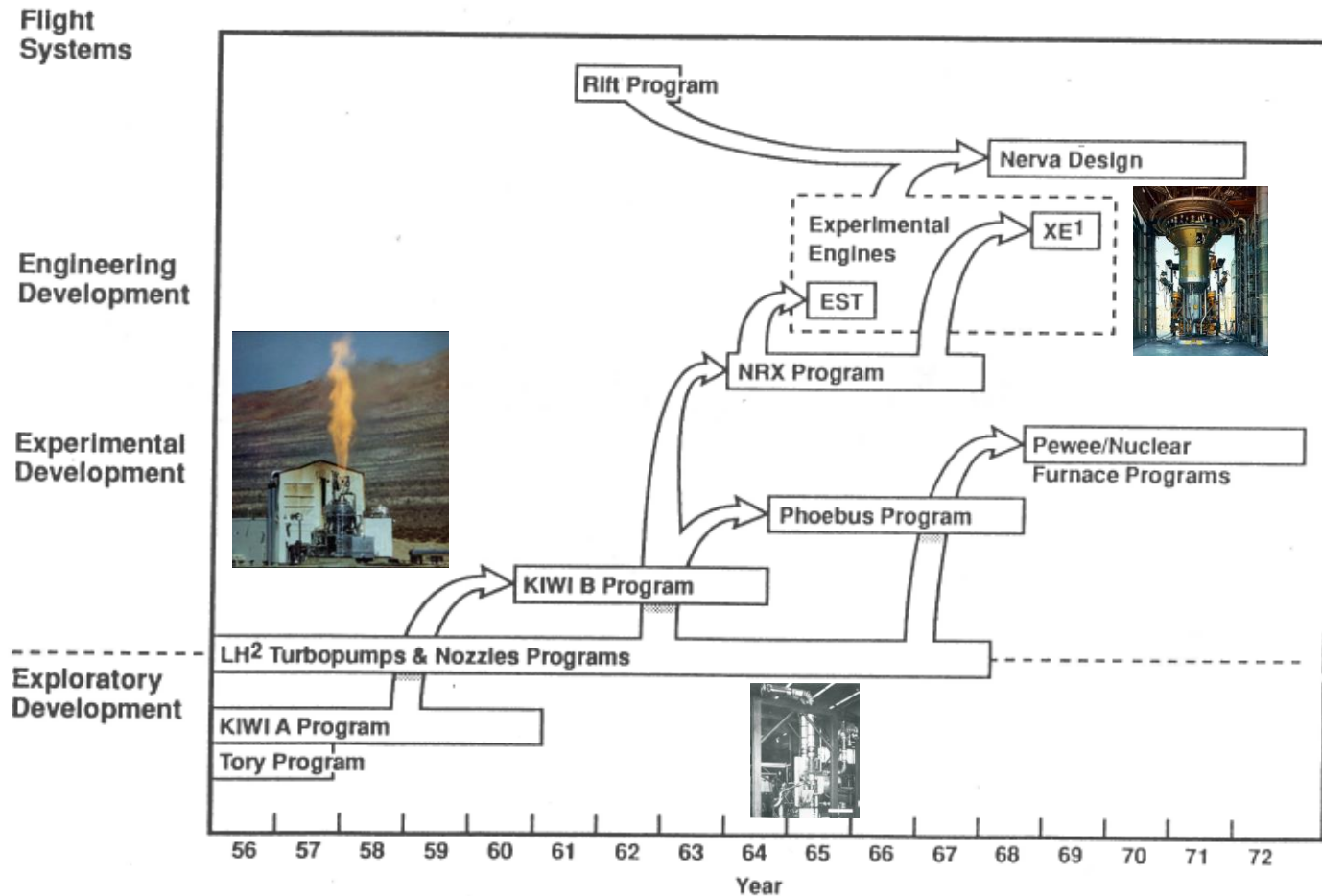
[1]

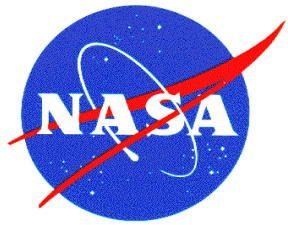


# Rover/NERVA TRL Evolution

[2]

TRL2  TRL6





# Past Rover/NERVA Ground Test Infrastructure at Nevada Test Site



Engine Maintenance Assembly and Disassembly (E-MAD).



Test Cell "A"

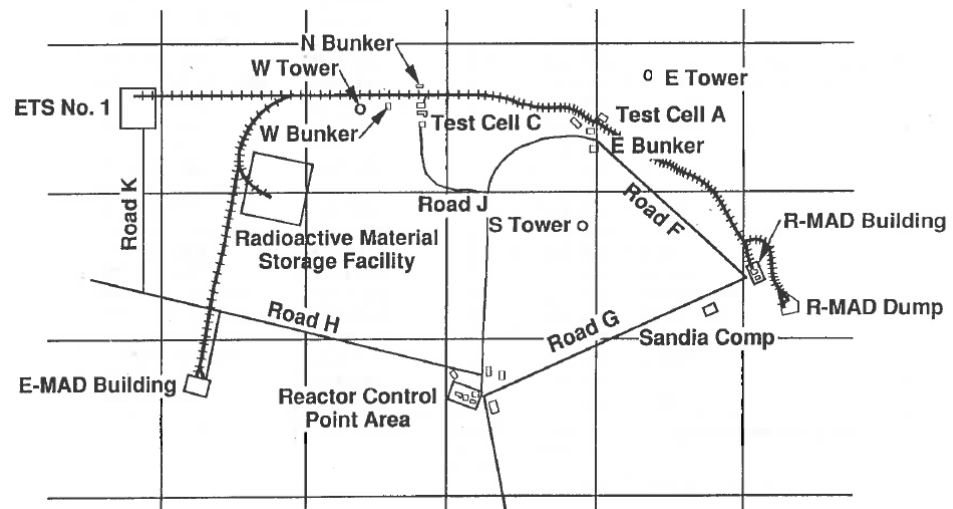


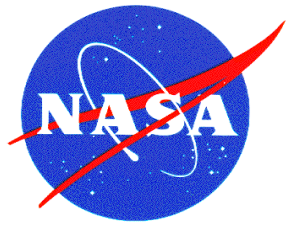
Test Cell "C"  
With two 500,000 gallon dewars of LH2

[3]

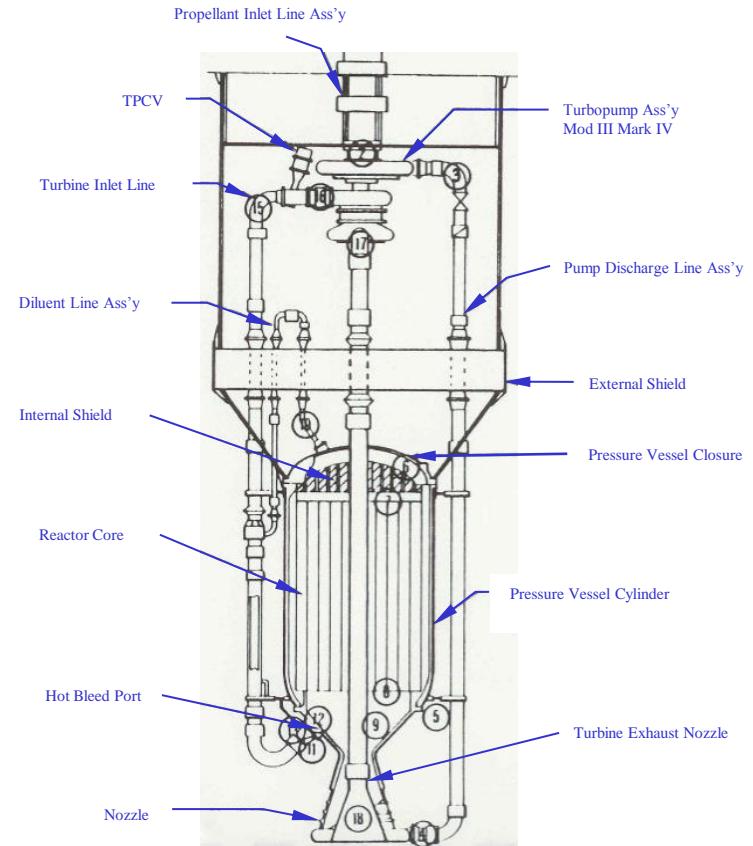


Engine Test Stand-1

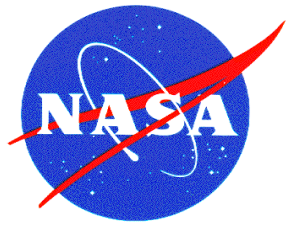




# ***XE' Experimental Engine- TRL 6***

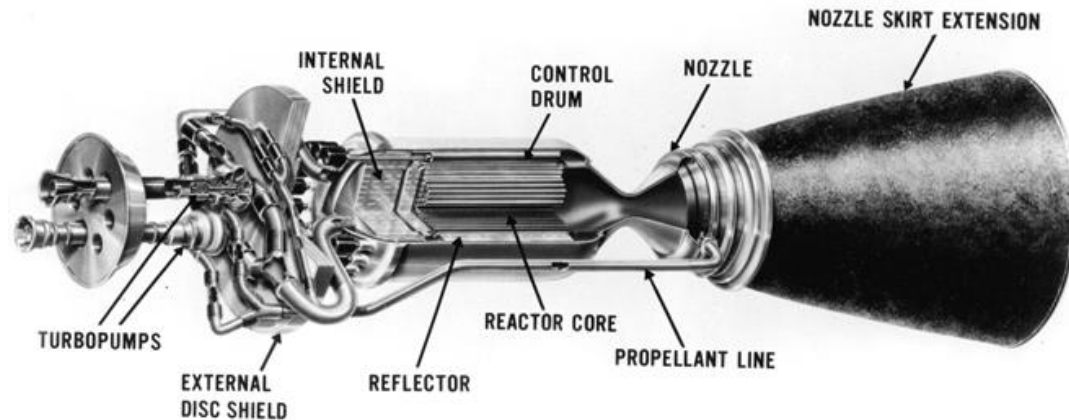
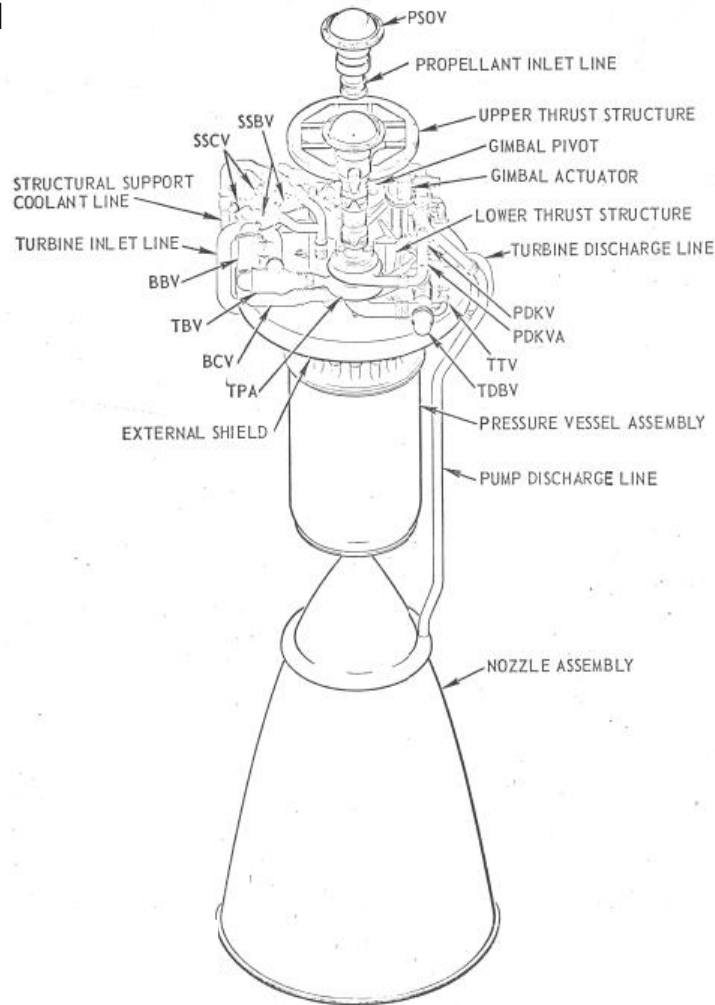


- 55430 lbs thrust
- 1140 MW power using NRX-A5 type fuel
- Hot-bleed-cycle in flight type configuration
- 28 restarts in 1969
- 11 minutes at full power
- Optimum startup and shutdown sequence demonstrated [4]

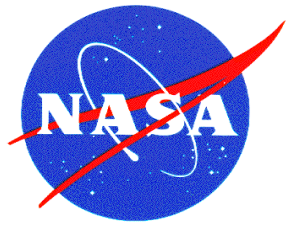


# NERVA Flight Engine for TRL 7 Goal

[5]

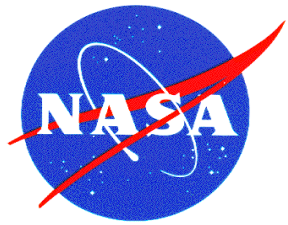


- Thrust 75,000 lbf
- Isp 825sec
- Chamber Pressure 450 psi
- 60 startups
- Minimum 10hr at rated temperature
- Design specs ready to go before program canceled



# ***Where are we Now with NTP?***

- Rover/NERVA program canceled in 1973 before flight demo
- Most Rover/NERVA ground test infrastructure too old or gone
- Only a few SME's from Rover/NERVA still around
- Hundreds of NTP reports in the archives
- Other past NTP efforts lasted a few years before being canceled (e.g., Space Nuclear Thermal Propulsion-SNTP, Space Exploration Initiative-SEI, etc).
- NTP always has been considered for human missions to Mars.
- NTP program funded by NASA Advanced Exploration Systems Office for last 3 years and still on-going



# *Why has the NTP TRL gone down?*

- Reactor fuel element design requirements and material “recipes” have changed
- Engine operating cycle modified
- Other misc modifications to components and subsystems



J-2 Rocket Engine from Apollo

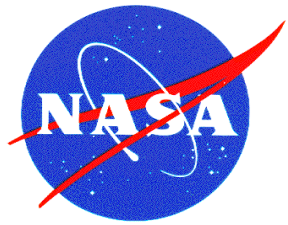
## Lessons learned from J-2X



Modifications to high TRL system design and operating requirements can reduce the TRL and require redevelopment and recertification

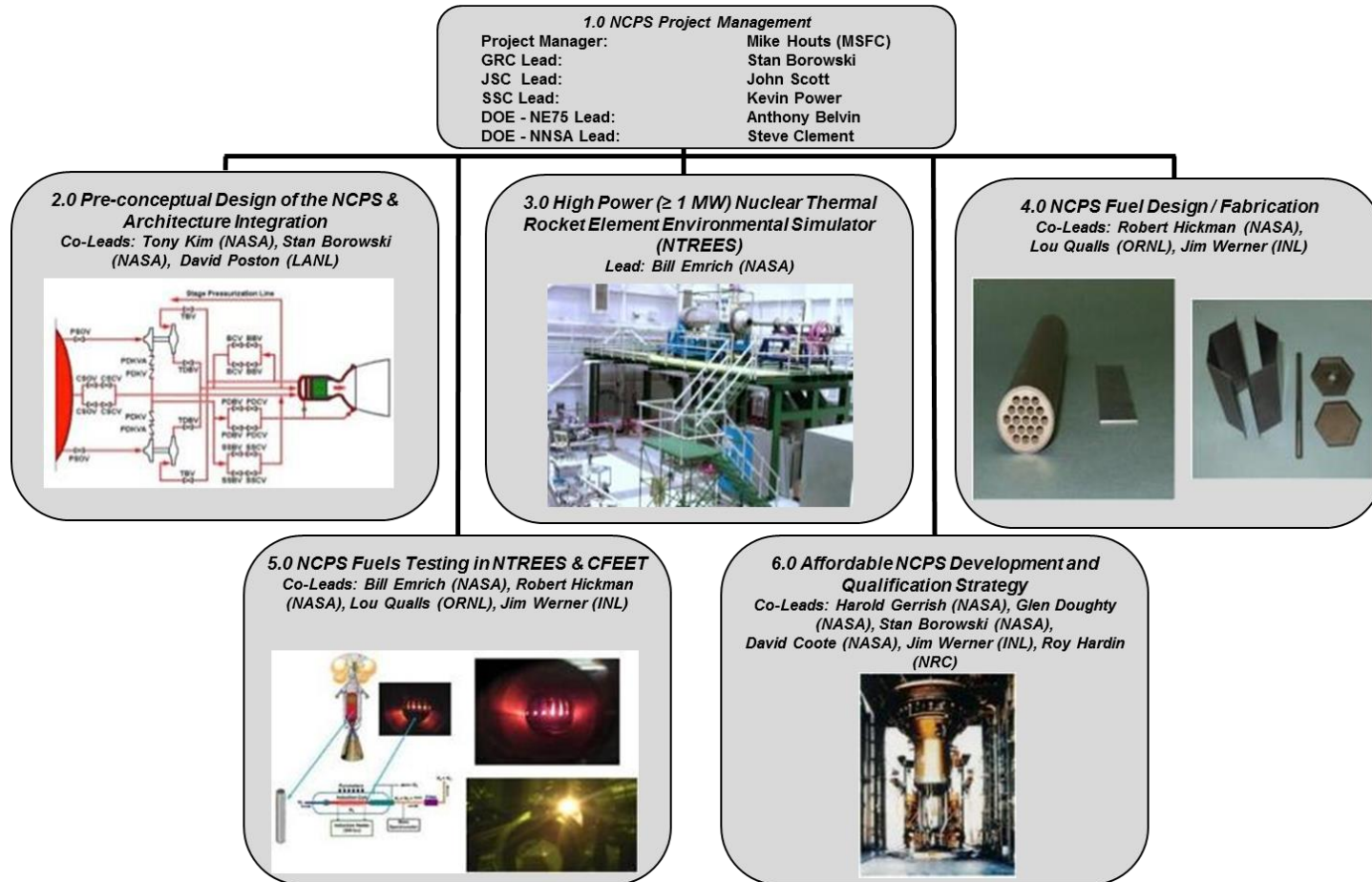


J-2X Rocket Engine for Constellation

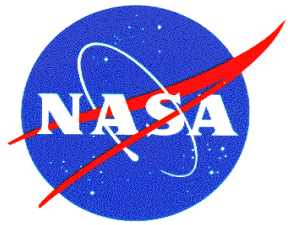


# Nuclear Thermal Propulsion Program

[6]

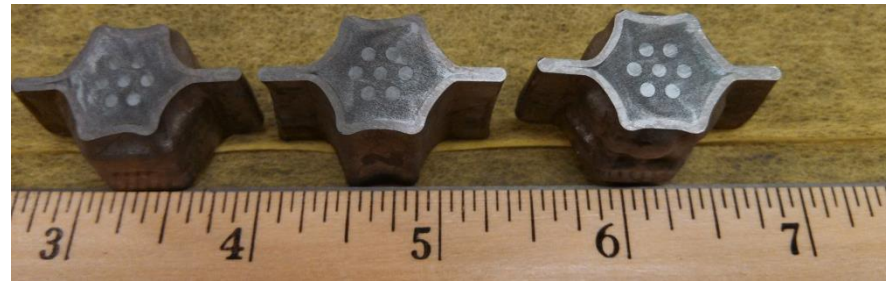


The goal of the program is to establish adequate confidence in the affordability and viability of NTP such that it is seriously considered as a baseline technology for future NASA human exploration missions with emphasis on missions to Mars in the 2030's



# W/UO<sub>2</sub> CERMET Fuel Element Fabrication: 7 Channel Element with Depleted Uranium

[6]



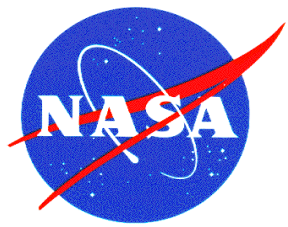
Above left/right: 7 channel W-UO<sub>2</sub> FE during HIP process

Above/Below: 7 channel WUO<sub>2</sub> fuel element post HIP and cross sections



Left & above: LANL sample post fill and closeout prior to shipping





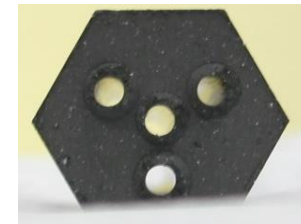
# Coated Graphite Composite Development (ORNL)



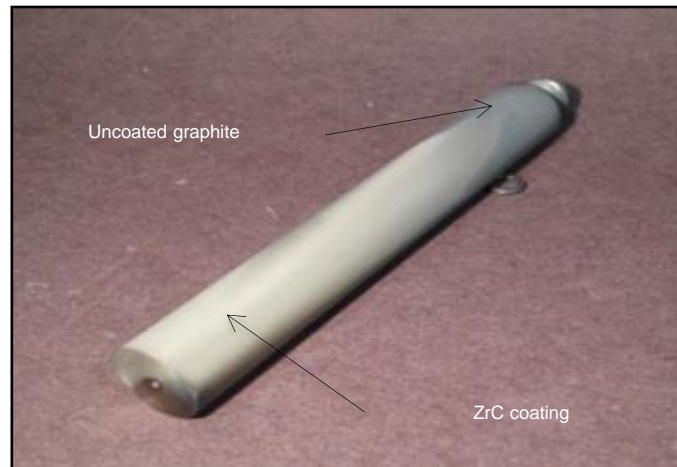
Above: Members of Oak Ridge National Laboratory fuels team with the graphite extruder; Left: Graphite extruder with vent lines installed for DU capability



[6]



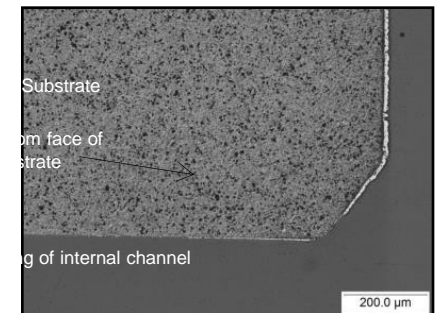
Above and Left: Extrusion samples using carbon-matrix/Ha blend .75" across flats, .125" coolant channels

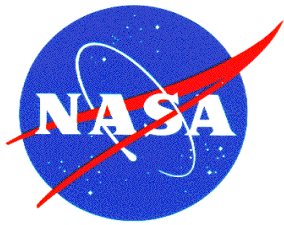


Above: Test Piece highlighting ZrC Coating  
Right: Coating primarily on external surface



Right: Layoff base / Graphite insert



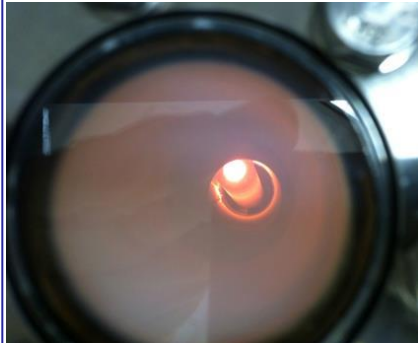


# Compact Fuel Element Environmental Tester (CFEET) ~ TRL 3

## CFEET System 50 kW Buildup & Checkout



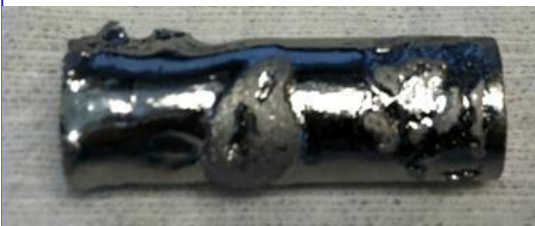
Completed CFEET system. Ready for W-UO<sub>2</sub> and H<sub>2</sub> testing



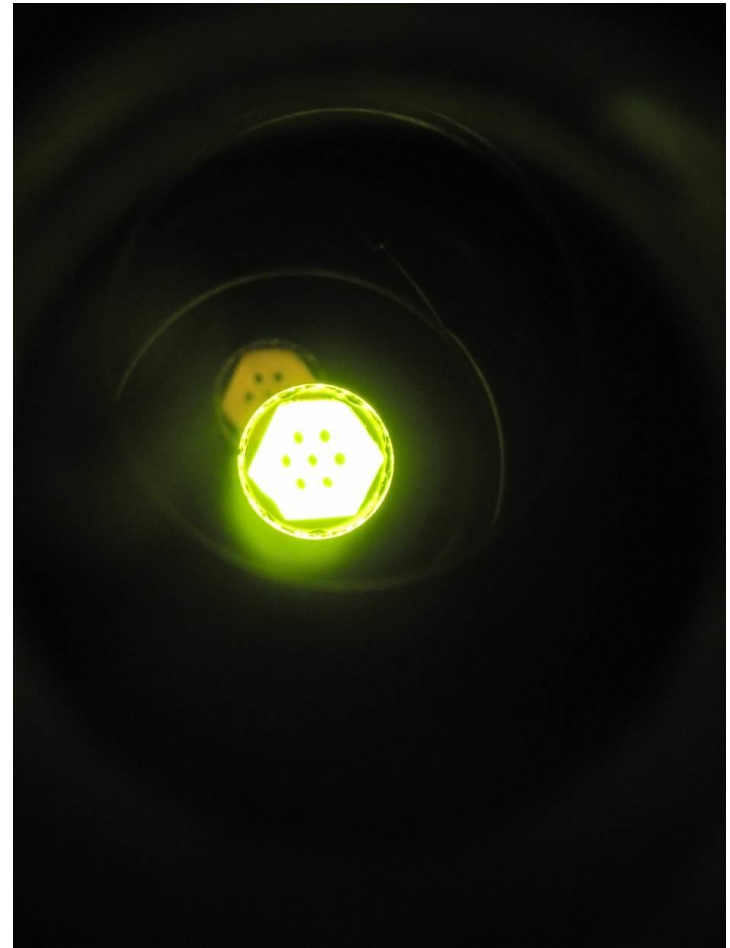
Left: View looking down into the CFEET chamber during shakeout run 1. BN insulator and bright orange sample inside



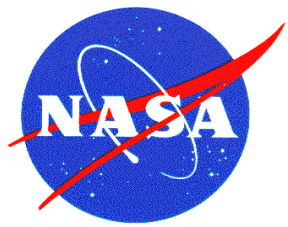
Above/left: Pure W sample post shakeout run 2. Sample reached melting point (3695K) and was held in place by the BN insulator.



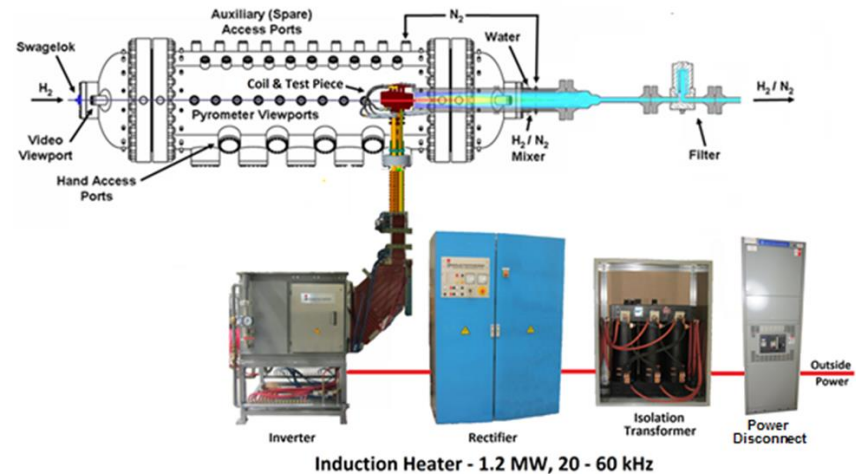
## Initial Testing of Short W/UO<sub>2</sub> Element



[6]



# Nuclear Thermal Rocket Element Environmental Simulator (NTREES) ~TRL 4

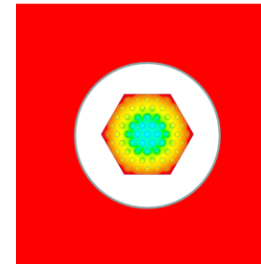


[7]

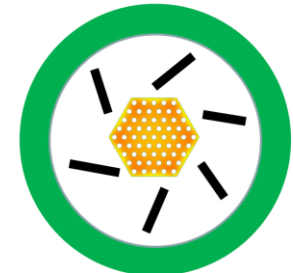
NTREES provides a cost effective method for rapidly screening of candidate material and examining thermal hydraulic performance.

- The NTREES is designed to mimic the conditions (minus the radiation) to which nuclear rocket fuel elements and other components would be subjected to during reactor operation.
- The NTREES consists of a water cooled ASME code stamped pressure vessel and its associated instrumentation coupled with inductive heaters to simulate the heat provided by the fission process.
- The NTREES has been designed to allow hydrogen gas to be injected into internal flow passages of a test article mounted in the chamber.

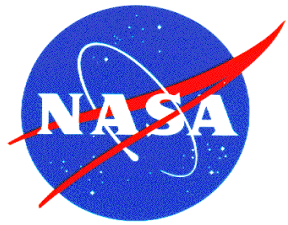
Current Coil  
Semi-adiabatic



New Coil Design  
Open with louvers



"Dial in"  
Boundary Conditions



# Future NTP Ground Testing Different than Rover/NERVA

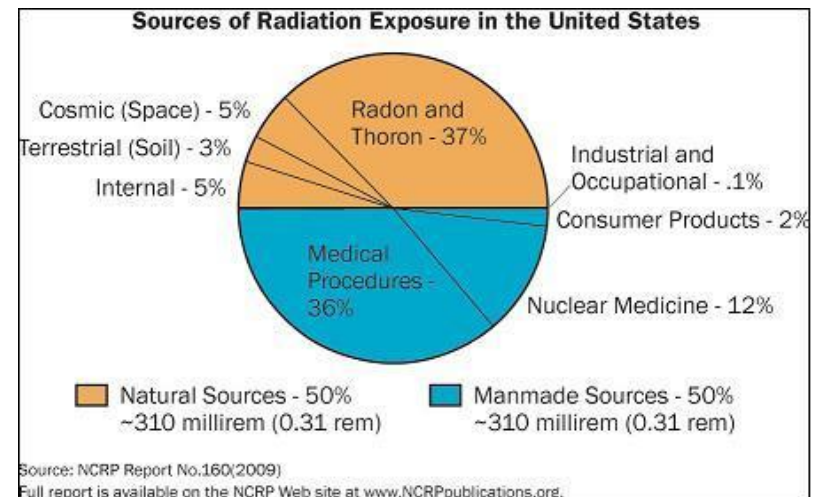


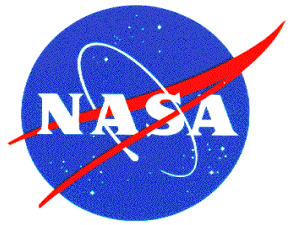
Rover/NERVA Open Air Testing

Radionuclides released into the air from DOE facilities are regulated by the National Emission Standards for Hazardous Air Pollutants (NESHAP 40 CFR61.90):

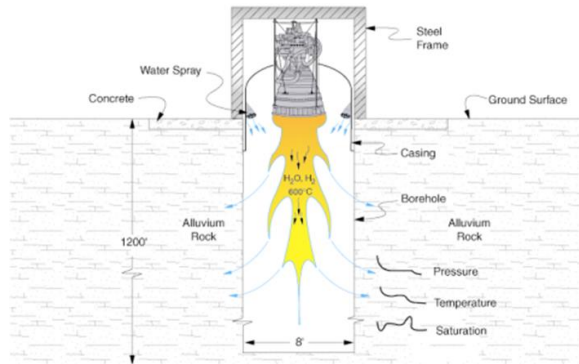
Emissions of radionuclides to the ambient air from Department of Energy facilities shall not exceed those amounts that would cause any member of the public to receive in any year an effective dose equivalent of 10 mrem/yr.

An effluent treatment system is needed for NTP to insure emissions remain within regulations under all possible operating scenarios

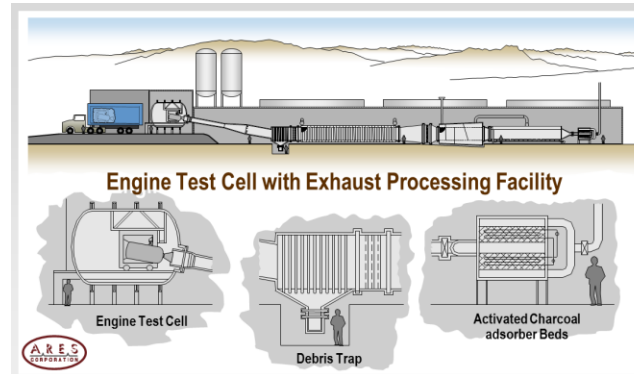




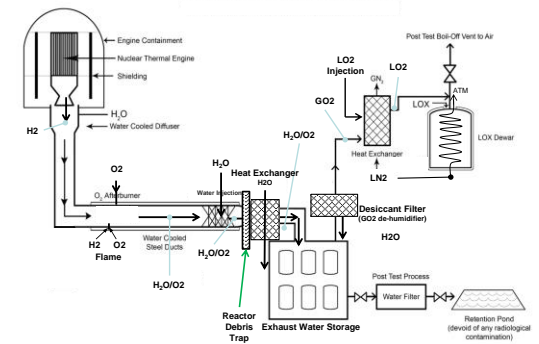
# Possible NTP Ground Test Options for TRL 6-8



Bore hole



Above ground scrubber with filters



Total containment with combustion and condensation

## ◆ Bore Hole

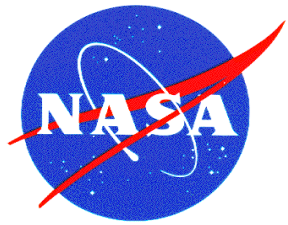
- Relies on permeability of desert alluvium soil to filter engine exhaust
  - Reports from Nevada Test Site show significant effects of water saturation, turbulent flow rate, hole depth, and pressures on soil permeability.

## ◆ Above Ground Scrubber

- Engine exhaust is filtered of radioactive aerosols and noble gases and directly flared to atmosphere
  - Nuclear Furnace (NF-1) ground test scrubber successfully tested at the end of Rover/NERVA project
  - DOE and ASME standards available for nuclear air cleaning and gaseous waste treatment

## ◆ Total Containment

- Engine hydrogen exhaust is burned at high temperatures with oxygen and produces steam to be cooled, condensed, and collected for controlled processing and disposal
  - All analyses to date indicate system will reliability and economically accomplish task



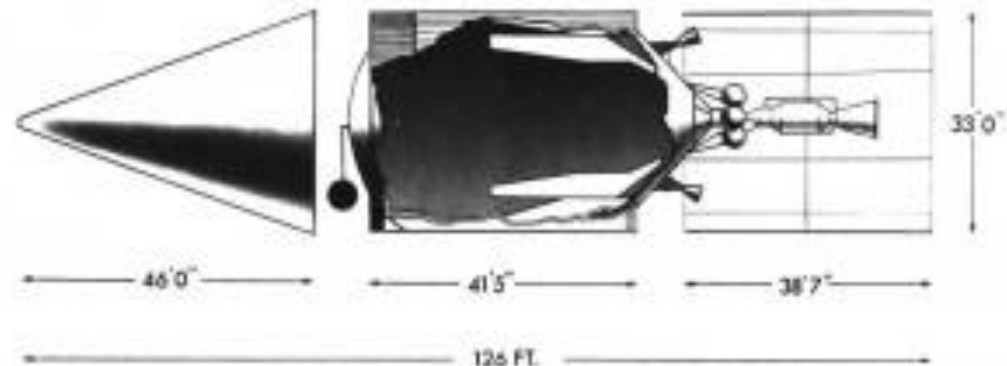
# Possible Prototype Flight Test for TRL 6-7

Prototype flight test demonstrates the following:

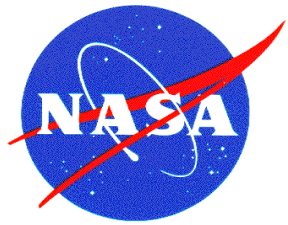
[8,9]

- System operation at reduced performance requirements
- Full nozzle expansion
- Radiate heat to space,
- Perform thrust vector control with engine operating,
- Validate reactor operation without effects from facility surroundings
- Monitor radiation effects on stage
- Exposure to space environment effects
- Engine inspection with space telerobotics
- Nuclear Safety Launch Approval

## INBOARD PROFILE OF RIFT

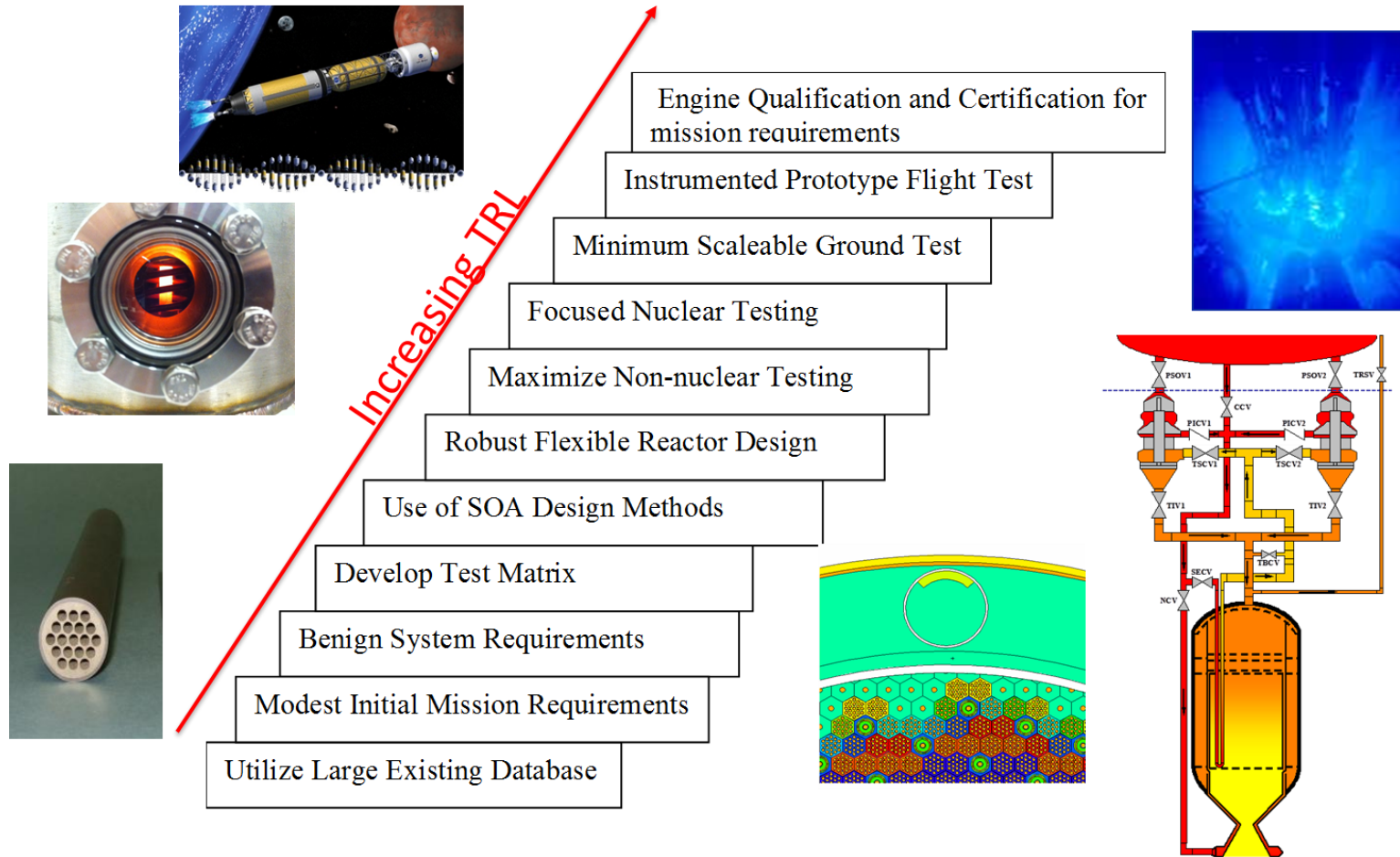


Also, Lessons Learned from ARES 1-X and Reactor in Flight Test (RIFT)

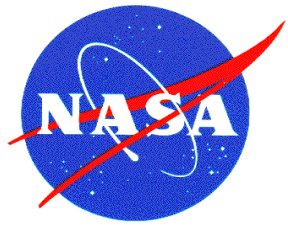


# Summary

[9]



Accounting for all the factors which influence the development plan and quantify the factors based on experience, analysis, analogies or similarities, will build greater justification with less uncertainty to have an authority to proceed with NTP development



# ***References***

1. Angelo, J. A., Buden, D., "Space Nuclear Power", OrbitBook Company 1985, p179-181, 184, 187, 188.
2. Gunn, S. V., "Development of Nuclear Rocket Engine Technology" MSFC NTP short course, 1992, section 14 page 4, 6, 27.
3. Gerrish, H.P., "Nuclear Thermal Propulsion Ground Test History", Nuclear Emerging Technologies for Space Conference, February 2014.
4. Finseth, J. L., "Overview of Rover Engine Tests- Final Report", NAS 8-37814, 1991.
5. NERVA Engine Reference Data, S130-CP-090290AF1, Aerojet, September 1970.
6. Houts, M., et al, "The Nuclear Cryogenic Propulsion Stage", AIAA Joint Propulsion conference, July 2014.
7. Emrich, W.J., "Initial Operation and Shakedown of the Nuclear Thermal Rocket Element Environmental Simulator (NTREES)", AIAA Joint Propulsion Conference, July 2014.
8. Fellows, W. S., "RIFT", Astronautics, December 1962, p38-42.
9. Gerrish, H.P., et al "Affordable Development and Qualification Strategy for Nuclear Thermal Propulsion", AIAA Joint Propulsion Conference, July 2013.